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SOLAR RADIO BURSTS, PROTON EVENTS AND GEOMAGNETIC ACTIVITY

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Abstract

The relationships between type II, type IV, microwave bursts and geomagnetic activity have been studied using data from various observatories compiled in the Solar-Geophysical Data over the period 1968-1982. It is found that type II bursts follow the trend of solar activity in general, more bursts occurring during periods of high solar activity. A similar trend is also seen with type IV bursts but their occurrence frequency is smaller than that of type II bursts. Superposed epoch analysis of geomagnetic activity index A_p before and after the events shows no dependence on type II bursts but the relationship with A_p improves following type II/IV bursts and a still better improvement is observed with type II bursts associated with moving type IV events. The position of type II burst on the solar disk does not seem to affect the A_p values significantly. Similar analysis carried out on the days of occurrence of solar proton events during 1970-1979 showed that an enhancement in A_p index on the second/third day is clearly seen in some years but not in all. But on the average, A_p shows significant increase if we consider longer periods i.e. 5 to 10 years.

Introduction

Attempts have been made in the past to associate visible events and phenomena that occur on the Sun's disk to geomagnetic storm activity. There exists a large amount of literature on this topic, especially after the International Geophysical Year (1957-58) when many coordinated measurements were carried out. Despite these efforts, no clear picture has emerged regarding the causative mechanisms of geomagnetic disturbances although some broad understanding has been acheived in this regard. Now, with high spatial resolution observations of active regions and flares becoming increasingly available in the radio, optical and x-ray domain, it is important to search for more definitive clues for a relationship between solar phenomena and geomagnetic storm activity.

Solar flares of optical importance 2 and 3 are known to be generally followed by sudden commencement (SC) type geomagnetic storms within 1 to 3 days, provided these flares occur within 45^{o} from the disk center and are associated with intense metric bursts (see for example: Dodson et al 1953; Dodson and Hedeman 1958; Kundu 1962, Kundu 1965). The geomagnetic disturbance characterized by index A_p or K_p shows a large increase on the second or third day after the flare. The average time interval between the occurrence of a flare and the start of the geomagnetic storm is about 54 hours for large flares and about 63 hours for flares of importance 1 (Dodson and Hedeman 1958). On the other hand, Hakura (1958) and Simon (1960) showed that only the flares associated with intense cm-g bursts are significantly correlated with geomagnetic activity and under such conditions the position of the flare on the sun's disk does not appear to be significant. Attempts have also been made to link filaments and their disappearance with geomagnetic activity (see Wright and McNamara, 1983 and references therein). Wright and McNamara (1983)

have found that the geomagnetic activity characaterized by A_p is enhanced typically 3 to 6 days after the disappearance of large filaments. The average delay is shorter during solar maximum than during solar minimum and depends upon the longitudes of the filaments.

Another line of approach to study this problem has been by using solar radio burst information. The geomagnetic activity of flares seems to be related to radio emissive property of the active regions in which they originate. The central meridian passage (CMP) of active regions (R-regions) giving flares of importance 3 and 3+ on the central part of the disk is followed by a distinct increase of geomagnetic activity, whereas the passage of quiet regions (Q-regions) giving the same proportion of 3 and 3+ central flares is followed rather by a decrease of the geomagnetic activity. The radio emissive property appears to be more important than the position of the flare on the solar disk. The noncentral flares occurring on R-regions are also associated with an increase of geomagnetic activity (Kundu 1962; Kundu 1965). Dodson et al (1953) found that flares with 200 MHz bursts of great intensity during the pre-maximum phase of the flare were frequently followed within 1 to 4 days by SC geomagnetic storms. Major outbursts at 200 MHz having no appreciable second part after the flare maximum produced no geomagnetic storms, or if any, only weak ones and the bursts having a strong second part are more likely to cause intense geomagnetic storms (Sinno 1959). A major early burst on meter waves is really a type II burst, whereas the second part of the event is the type IV burst. A type II burst is plasma radiation produced by shock wave moving through the corona with speeds of about 1000 kms^{-1}, whereas a type IV burst is due to gyrosynchrotron radiation of energetic electrons within the plasma cloud moving behind the shock wave (Kundu 1965; Wild and Smerd 1972). Thus, type II and type IV bursts on meter

waves provide direct evidence of the existence of a corpuscular cloud capable of causing a geomagnetic storm. Although important flares are related to an increase of geomagnetic activity, it is only the flares associated with intense cm-λ bursts (type IVA) which are significantly correlated with geomagnetic activity (Hakura 1958; Simon 1960; Kundu 1962).

Since shock waves with speeds of f 10^3 kms^{-1} are thought to be responsible for type II bursts, it is logical to identify these shocks with those causing magnetic storms and aurorae on the earth. Roberts (1959) showed that the geomagnetic index A_p values were significantly high from 1.5 to 2.5 days after a type II burst, the maximum value being about 1.5 times the quiet value. Maxwell et al. (1959) showed that only 45 percent of type II bursts were followed by magnetic storms and aurorae. This association increases if type II burst is associated with type IV bursts on meter waves (McLean 1959). The type IV radiation consists of three distinct phases (Kundu 1961a). The meter-wave phase is usually associated with, and follows, a type II burst. This moving plasma cloud carrying frozen-in magnetic fields ultimately becomes the magnetic storm cloud, travelling with the initial type IV velocity which is identified as moving type IV. The present study attempts to find inter-relationships between type II, type IV, microwave bursts, proton events and geomagnetic activity.

Data Analysis and Results

The main sources of data for radio, optical, geomagnetic activity and other information are derived from the Solar Geophysical Data (SGD) published by NOAA, Boulder. Our present statistical study is based upon data from 1968 to 1981. We have also taken into consideration the data published by Culgoora Radio Observatory (Robinson et al 1983), UAG Reports No. 14, 52 and 80 (Dodson

and Hedeman 1971, 1975, 1981), proton event lists of Shea and Smart (1977, 1979), Krivsky (1977), Solar Proton Events 1970-1979 prepared by the USSR Academy of Sciences, Moscow, 1983 and the microwave data of Toyokawa Observatory in Japan (Enome, private communication). We have used the superposed epoch method of analysis for the geomagnetic activity A_p values listed in SGD as daily average geomagnetic indices. Generally, the values for six days before and six days after the "0" epoch day have been considered here. The "0" epoch day was taken to be the day on which type II and type IV (moving and stationary) associated with proton events and microwave bursts were recorded. The results of this analysis are presented in Parts I and II of this paper.

Part I

Solar Radio Bursts and Geomagnetic Activity

I. Type II bursts and Solar Activity

We have studied as a function of solar activity the occurrence of type II and type IV bursts including moving type IV bursts (type IVm) observed at Culgoora, where long series of systematic observations exist, including the radioheliograph positional information at 43, 80 and 160 MHz (Robinson et al 1983). It should be noted that in the list of major meter wave solar bursts published by Robinson et al (1983), continuum bursts following type II bursts are stationary type IV bursts (type IVs). Figure 1(a) shows a plot of the number of bursts of type II, type IVs and type IVm from 1968 to 1981 and Figure 1(b) shows the annual mean sunspot number during the same period. Type II burst occurrence corresponds very well with the sunspot number, that is,

maximum number of bursts occur during maximum solar activity and minimum during low solar activity years. The number of type II bursts was f 50 in 1970 and f 70 in 1980 when the sunspot number was 100 and 150 respectively at the peak of solar activity cycle. There is a general trend of this behavior even in the case of type IVs bursts. However, their occurrence frequency is less than 50 percent of that of type II bursts. The behavior and association of type IVm with type II and solar activity are less clear; in fact their occurrence frequency is only 5-10 per cent of that of type II occurrence. There appears to be no systematic variation of their occurrence frequency with solar activity.

II. Type II Bursts and Geomagnetic Activity

Since type II bursts are generated by shock waves moving through the corona with speeds of f 1000 kms^{-1}, they are likely to be associated with the occurrence of geomagnetic storms and aurorae at the earth. Therefore, taking the days of occurrence of type II burst as "0" epoch day, we have made superposed epoch analysis of A_p geomagnetic index values on six days before and six days after the "0" epoch day. We have considered all type II bursts reported in SGD in 1980 and categorized them according to their intensity 1, 2 and 3. There were 51, 59 and 43 bursts in intensity categories 1, 2 and 3 respectively. Figure 2(a) shows the result of such an analysis for 1980. The type II burst occurrence, regardless of its intensity category 1, 2 or 3, does not show any significant causal relationship with geomagnetic activity even up to 6 days after the burst occurrence. This is contrary to the results of Roberts (1959) and Maxwell et al. (1959), who showed that the A_p values were significantly high from 1.5 to 2.5 days after type II bursts. We shall discuss this result later. We have carried out a similar analysis for type II

bursts for epoch days during 1979 and 1981 for intensity 3 bursts only. Figure 2(b) shows the results for 39 intensity 3 bursts observed in 1979 and 49 intensity 3 bursts observed in 1981. Again, we find no significant association with A_p for up to 6 days after the type II burst occurrence. This result is important, since it implies that type II bursts alone do not affect geomagnetic storm activity.

III. Type II/Type IV Bursts and Geomagnetic Activity

Maxwell et al. (1959) and McLean (1959) showed that the correlation of geomagnetic storms is high with metric type IV/type II bursts. For the period 1979-1981, we found 35, 14 and 35 type II bursts associated with type IV, for which we have done superposed analysis. A_p index shows better association with type IV/type II bursts than with type II only (Fig. 3). A_p peaks 3-5 days after the type II/type IV occurrence. However, the peak in A_p after the "0" epoch days is not clearly observed in the 1981 data, which may imply that the type IV associated with type II was not of appropriate intensity.

The effect of type II and type II/type IV bursts with associated Hα flares occurring within ± 45° heliographic longitudes on geomagnetic activity, is shown in Figures 4, 5 and 6 for 1978, 1979 and 1980 respectively, using the bursts observed at Culgoora. The type II/type IV bursts have also been grouped into the east and west longitude zones. It can be seen that type II/IV bursts are, in general, effective in producing enhanced geomagnetic activity from 1 to 5 days after the "0" epoch day, whereas type II bursts alone do not appear to be effective in the enhancement of A_p index.

IV. Type II, Microwave Burst and Geomagnetic Activity

Hakura (1958), Simon (1960) and Kundu (1962) showed that only the flares associated with intense centimeter-wavelength bursts (type IVA) are significantly related to geomagnetic activity and that this relation does not seem to depend on the disk position of the correspsonding flares. To study this relation further, we have used type II bursts associated with microwave bursts. The analysis of 7, 14 and 27 cases of type II associated microwave bursts in 1979, 1980 and 1981 respectively, shows that the A_p values do not show significant dependence on such bursts, although a broad maximum in A_p was seen in 1980 from three to five days after the epoch day (Figure 7).

V. Moving Type IV and Geomagnetic Activity

Kai (1979) made a statistical study of 31 moving type IV bursts observed at Culgoora up to 1975 and found that their relation to other phenomena like proton events and geomagnetic activity is rather poor. He found that a small percentage of moving type IV bursts have velocities of the order of 10^3 km s^{-1} and are associated with MHD shocks i.e. type II bursts and the slower moving type IV bursts are manifestations of isolated plasmoid type and are not associated with type II. It was of interest to see with the availability of more extended data up to 1981 whether or not if these bursts were effective in producing geomagnetic activity. During the period 1968 to 1981, 46 moving type IV bursts were observed by the radioheliograph at Culgoora (Robinson et al. 1983). Some of them were often too weak to be seen in radio spectrograph records. Taking their observed day as "0" epoch day, we made the superposed epoch analysis of A_p values for 44 events, some associated with type II bursts (28 events) and the remainder not associated with type II bursts (16 events). The geomagnetic activity shows a small peak on the third day of the

moving type IVm/type II burst occurrence (see Fig. 8). For the moving type IV with no type II bursts, no enhanced geomagnetic activity was observed up to 6 days after their occurrence.

We have divided type IVm/type II into two categories: those with type II drift velocity greater and less than 1000 km s^{-1} observed at Culgoora during 1968-1973 (Kai 1979), and studied their effects on geomagnetic activity. Two maxima in geomagnetic activity (Fig. 9) seem to occur on the third and sixth (seventh) day after the event occurrence. The second maximum is substantially larger than the first one for the high speed type II. The two maxima are sharp in the case of slow speed type II; for the high speed type II, the second maximum is broad and peaks on the seventh day, and the A_p value remains high even on the tenth day.

VI. Type II Burst Positions and Geomagnetic Activity

In order to study the dependence of type II burst position on geomagnetic activity, we have used positional information of 48 weak type II bursts observed with the Culgoora radioheliograph during 1975-1979 and published in SGD. These data are available in the form of position angle and distance from the sun's center. For most of the bursts used by us, the flares occurred behind the limb or no flares were reported in SGD. Of the 48 events in this category, 23 events occurred on the western hemisphere and 25 on the eastern hemisphere. The A_p values are depressed in the post-epoch period from 2 to 6 days as compared to the pre-epoch period (Fig. 10). The depression is large and wide for all the 48 events and for the bursts occurring on the western hemisphere whereas it is small and shallow for the bursts occurring on the eastern hemisphere.

During 1978, about 42 type II burst positions were reported in SGD from Culgoora. We grouped the type II bursts in southern, northern, eastern and western hemispheres of the sun and also according to the four quadrants. The results of superposed epoch analysis are shown in Figures 11 and 12. No significant dependence of A_p values on the burst position was observed.

VII. Solar Hard X-ray Bursts and Geomagnetic Activity.

Since solar hard X-ray bursts and microwave bursts are known to be highly correlated temporally (Kundu 1961b), we considered it appropriate to see how these bursts influence the geomagnetic activity. Although more than 6000 solar X-ray bursts (large and small) have been observed by the SMM satellite since its launch in 1980 (Dennis et al 1983), we chose only the intense ones with peak counts greater than 10^4 per second. There were 18, 23 and 16 events of this type in 1980, 1981 and 1982 respectively and the results of superposed epoch analysis are shown in Figure 13. The enhancement in A_p index after epoch is not very pronounced as one would have expected but it does show a peak on the fourth day in 1980 and 1982 though not in 1981.

Part II

Solar Proton Events and Geomagnetic Activity

Data Analysis and Results

In this part we shall discuss the relationship between solar proton events (SPE) and geomagnetic storm activity. For this study we have used a catalog of proton events, prepared by the USSR Academy of Sciences, Moscow for the period 1970-1979. This catalog also contains lists of solar flares, radio

bursts, particle events, their fluxes, SC of geomagnetic storms and other relevant information from groundbased and satellite measurements. A total of 113 solar proton flare events have been listed in the catalog for the ten year period 1970-1979 and they have been treated as "zero" epoch day on their day of occurrence for the superposed epoch analysis of A_p values up to six days before and six days after that epoch.

Figure 14 shows the distribution of solar proton events over the period 1970 to 1979, as a function of year. The number of events ranges from 3 in 1975 to 28 in 1978. There is no obvious one to one correspondence of this number with solar activity, although, in general the occurrence frequency of the proton events is larger during high solar activity years. Also shown in the Figure are the number of SPE associated with type II, type IV, microwave bursts having greater than 200 sfu (1 sfu = 10^{-22} wm^{-2} Hz^{-1}) and those associated with SC of geomagnetic storms. In all these cases, the frequency of occurrence was less than that of SPE. In Figure 15, are shown the occurrence frequencies of SPE associated with type II, type IV, microwave bursts and SC of geomagnetic storms as a percentage of the total SPE observed. We find that when the SPE occurrences are low as in 1973 and 1975, their association with type II and type IV is 100 percent, whereas in 1978 and 1979 when the SPE's are more frequent, their association with type II and type IV is only about 60 to 80 percent. The situation is not the same for SPE associated with microwave bursts and SC. Here the rate of occurrence is about 50% or lower and shows less clear dependence on the total number of SPE's observed.

Superposed epoch analysis of daily average A_p values for six days before and six days after the "0" epoch day on which the solar proton event occurred was carried out on a year to year basis from 1970 to 1979. It should be noted

that if more than one SPE occurred on a particular day, we have treated them as only one event for superposed epoch analysis.

Figure 16 shows the results of analysis for the two five year periods and for the entire ten year period. In each case, the geomagnetic activity shows significant enhancement on the second/third day after the "0" epoch day of the solar proton event. The results shown in Figure 16 are statistically more significant since the number of events is large over the longer period. Such enhancement is not clearly seen on a year to year basis, because only a few proton events occur per year.

In order to study the relationship between the geomagnetic activity index A_p and solar proton events associated with solar raido bursts, we have considered only the SPE´s in 1978 and 1979 when the number of events was fairly large. We have used the SPE associated with type II, type IV and microwave bursts as the "0" epoch day, and also those associated with microwave bursts having flux greater than 200 sfu as the "0" epoch day. The relationship improves considerably between A_p and SPE associated with microwave flux greater than 200 sfu (Figs. 17 and 18). We have not done the analysis using microwave bursts with still higher flux values, say, 500 sfu since the number of such events is small. Most of the SPE´s were associated with type IV and type II bursts, and we have not treated them separately. The results show considerable improvement in A_p enhancement after the epoch as can be seen in Figs. 17 and 18.

Discussion

We find that the problem of establishing a relationship between various solar phenomena such as radio bursts and proton events with geomagnetic activity is quite complex, although it appears clear that strong proton events

associated with type II/IV and microwave bursts do produce enhanced geomagnetic activity after 2-3 days of their occurrence.

The complexity in such correlative studies and isolating a particular phenomenon as a causative agency is rather formidable because we do not understand well information about the relationship between type II shocks and interplanetary shocks and other propagation effects from the sun to the earth. Some theoretical studies on the MHD modeling of solar-initiated shocks propagating through the interplanetary medium have been made (Dryer 1982) and these ideas have been applied to interpret the observations of August 1972 and April 1981 events (Smart et al 1984). But these ideas are still not widely used for lack of detailed coordinated groundbased and satellite observations under different solar conditions.

An interesting aspect on the geoefficiency of flares needs to be yet understood. A dependence of radio emission in large H-alpha flares on the orientation of the local solar magnetic field has been discussed by Roelof et al (1983). They showed that during 1967-1970, the greatness of flares was influenced by the orientation of the large scale (~ 100,000 km) magnetic field structures over the flare site. The meter wavelength flux was on the average an order of magnitude greater for flares with southward oriented magnetic fields than when it was directed northward. Pudovkin and Chertkov (1976) and Dodson et al (1982) showed that such flares were more efficient in producing geomagnetic disturbances. On the other hand, Wright and McNamara (1982) did not find significant differences between the energies of flares with northward, southward or east-west magnetic field and their subsequent geoefficiency.

Another index called comprehensive flare index (CFI) has been used by Dodson and Hedeman (1971, 1985, 1981) by combining optical, radio and

ionospheric effects of solar flares. They showed that the mean K_p values peaked on the second day after the occurrence of major flares with CFI greater than 10 during 1958-1959 but for flares with CFI less than 10, the geomagnetic index did not show any dependence. We have carried out similar analysis for flares with CFI greater 10 during 1975-1979. The A_p index shows a clear maximum on the third day of the occurrence of major flares with CFI greater than 10 and no dependence for CFI < 10 (Fig. 19), in agreement with the earlier findings of Dodson and Hedeman. This means that even large optical flares by themselves could not cause geomagnetic disturbances if they are not accompanied by type II, type IV, cm-λ and meter-λ bursts.

Out of a total of 103 solar proton events listed in the ten year period 1970-1979 and used in the present study, only about 50 per cent events are associated with Hα flares. The association of proton events with type II and type IV bursts is much higher (~ 80-90 per cent) than with H-alpha flares; their association with microwave bursts with flux greater than 200 sfu is about 50 per cent and with SC of storms less than 50 per cent.

Since the solar proton events and type II, type IV and microwave bursts show good association in a majority of cases (see Kundu and Haddock 1960), protons and electrons need to be accelerated to high energies to produce these events. Apart from the acceleration of particles at the flare site, protons could be accelerated in the interplanetary medium. Svestka and Fritzova-Svestkova (1974) found that all type II bursts they studied were associated with the production of interplanetary energetic protons. Kahler (1982), however, found that there were type II bursts not associated with proton events. Thus, many shocks producing type II bursts produce no interplanetary energetic protons. The occurrence of a decimetric or metric stationary type IV burst seems to be required for association with most proton events (Kahler

1982). Positional and structural information of type II/IV solar bursts may be useful in studies of this kind; however, such data are not yet widely available to permit a statistically significant study.

Conclusions

From the superposed epoch analysis of A_p values and taking type II, type IV, microwave bursts, proton events as epoch days, we find that a combination of proton events associated with type II/IV and microwave bursts seem to be the best candidate to produce high geomagnetic activity. Any single type of event may not be sufficient to produce any enhancement in A_p. Position of the type II radio burst on the solar disk does not appear to influence the geomagnetic activity significantly.

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Figure Captions

Figure 1. (a) Number of events of type II, type IVs and type IVm observed at Culgoora from 1968 to 1981. The occurrence frequency of type II bursts is seen to follow well the annual mean sunspot number R_z plotted in (b), whereas type IVs bursts occur much less frequently (~ 30%) than type II and type IVm far less frequently (~ 5%) than type II bursts.

Figure 2(a). Superposed epoch analysis of daily average geomagnetic index A_p six days before and six days after the "0" epoch day of type II burst occurrence of intensity 1, 2 and 3 in 1980. No obvious dependence of A_p index is seen for type II of intensity 1, 2 or 3, although a slight increase of A_p on the third day of type II burst of intensity 3 is observed.

Figure 2(b). A similar analysis of A_p values taking type II bursts of intensity 3 as "0" epochs in 1979 and 1981. A marginal increase, if any, in A_p on the second or third day is seen.

Figure 3. Superposed epoch analysis of A_p index for six days before and six days after the "0" epoch day for type II bursts associated with type IV bursts. Geomagnetic activity shows a marked increase between 3 and 5 days after the epoch day.

Figure 4. Superposed epoch analysis using type II and typeII/type IV bursts with associated Hα flares within ± 45° heliographic longitudes as "0" epoch in 1978. A_p shows enhancement after type II/type IV burst occurrence. Enhancement is more pronounced for cases in 0-45° west longitude than for east longitude cases.

Figure 5. Same as in Figure 4 for 1979. Here also A_p shows enhancement after type II/type IV burst occurrence, especially for cases in 0-45°W longitudes.

Figure 6. Same as in Figure 4 for 1980. Results show similar trend as in 1978 and 1979.

Figure 7. Results of similar analysis as in Figure 3 but using type II bursts associated with microwave bursts as "0" epoch day during 1979-1981. A_p variation before and after the "0" epoch day is not clear.

Figure 8. Superposed epoch analysis of A_p indices using type IVm events as "0" epoch from 1968 to 1981. Type IVm associated with type II appears to be a better indicator of geomagnetic activity, showing A_p maximum on the third day after the "0" day.

Figure 9. A similar analysis is shown for 1968-1973 taking moving type IV bursts associated with type II bursts having drift velocity greater and less than 1000 km s^{-1}. A_p shows two sharp peaks on the third and sixth day after the "0" day for lower drift velocity events and A_p reached a prominent maximum on the seventh day for the higher drift velocity events.

Figure 10. Superposed epoch analysis of A_p indices for 48 type II bursts for which positional information was available during 1975-1979. Of 48 such cases, 25 occurred on the eastern hemisphere and 23 on the western hemisphere of the sun's disk. A_p index shows depression after the second day of the "0" epoch day. The depression is more pronounced for the western hemisphere events than for the eastern hemisphere events.

Figure 11. Superposed epoch analysis of A_p values for 42 type II bursts in 1978 for which positional data of Culgoora were available from Solar Geophysical Data reports. Results are shown for bursts ocurring in southern, northern, western and eastern hemispheres of the sun. Last curve is for all bursts irrespective of their positions. No clear relationship with geomagnetic activity is seen.

Figure 12. Similar analysis as in Figure 11 but with type II burst positions in four different quadrants of the solar disk.

Figure 13. Superposed epoch analysis of A_p values on days of intense solar hard x-ray bursts with peak counts greater than 10^4 per sec. A_p shows enhancement on the fourth day after the epoch in 1980 and 1982 but not 1981.

Figure 14. Histogram of the number of occurrences of Solar Proton Events (SPE), SPE associated with type II, type IV, microwave bursts with flux greater tan 200 sfu and sudden commencement (SC) of geomagnetic storm during the years 1970 to 1979.

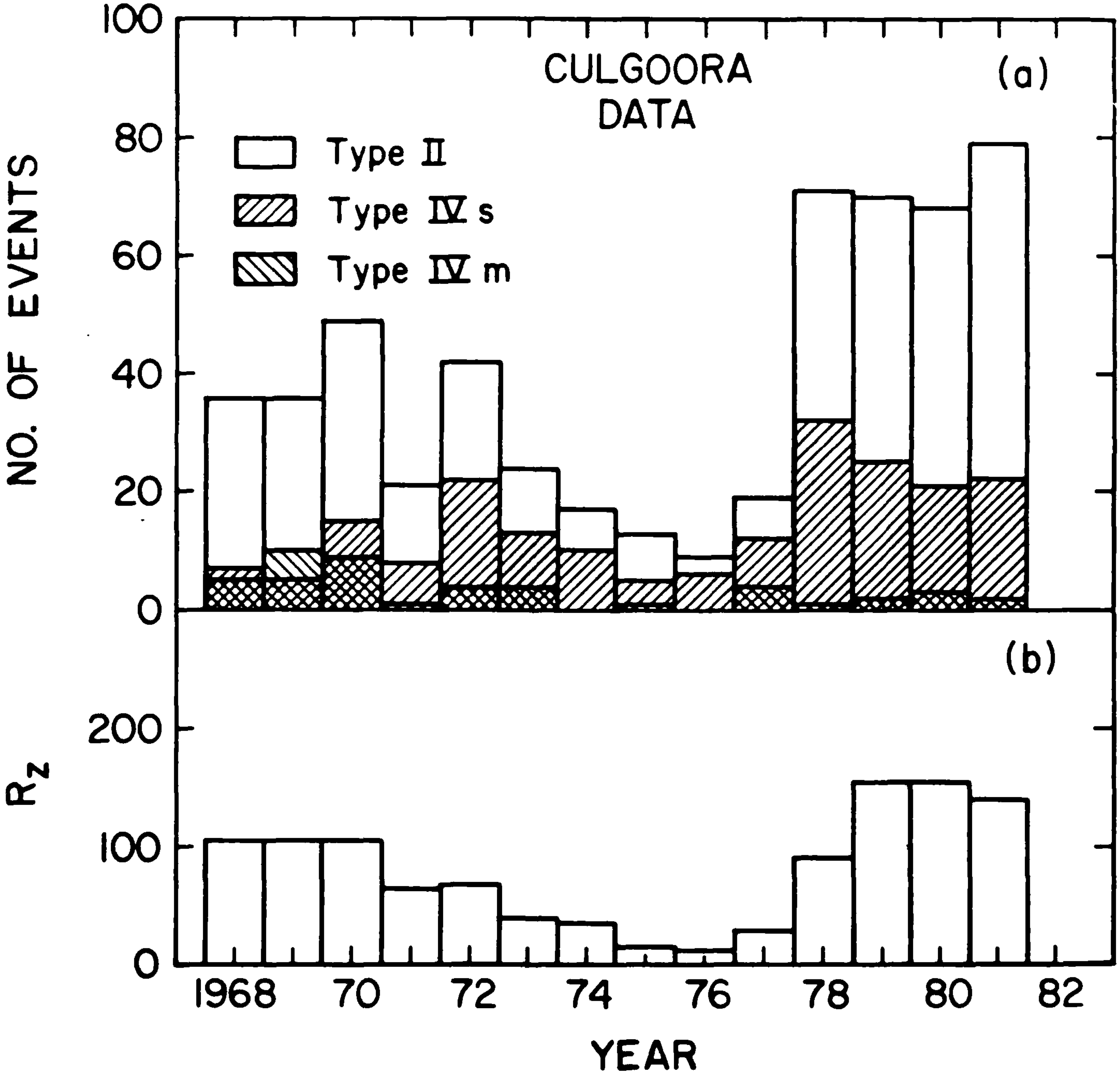
Figure 15. Same as in Figure 14 but the SPE associated events are expressed as percentage occurrence of total SPE observed each year from 1970 to 1979.

Figure 16. Superposed epoch analysis (a) for five years from 1970 to 1974, (b) for the next five year period 1974-1979, and (c) for ten years 1970-1979. In all cases, enhancement is clearly seen on the second/third day after the zero epoch day of the occurrence of SPE.

Figure 17. Superposed epoch analysis using proton events of 1978 associated with type II, type IV and all microwave bursts and with microwave bursts with flux greater than 200 sfu as "0" epoch day. The A_p index shows a prominent peak on the second/third day after the epoch.

Figure 18. Superposed epoch analysis of A_p values taking SPE in 1979 associated with type II, type IV and microwave bursts with flux > 200 sfu and with all flux values. Curve (a) shows a large but broader peak after the epoch and a sharp depression two days prior to the epoch.

Figure 19. Superposed epoch analysis of A_p index for major flares in 1975-1979 with CFI > 10 (49 cases) and with CFI between 6 and 10 (146 cases). A_p index shows enhanced peak on the third day after major flares with CFI > 10. There is no dependence when CFI is less than 10.



100
80
60
40
20
0
NO. OF EVENTS
CULGOORA
DATA
(a)
Type II
Type IV s
Type IV m
(b)
200
100
0
R_Z
1968
70
72
74
76
78
80
82
YEAR

Fig. 1

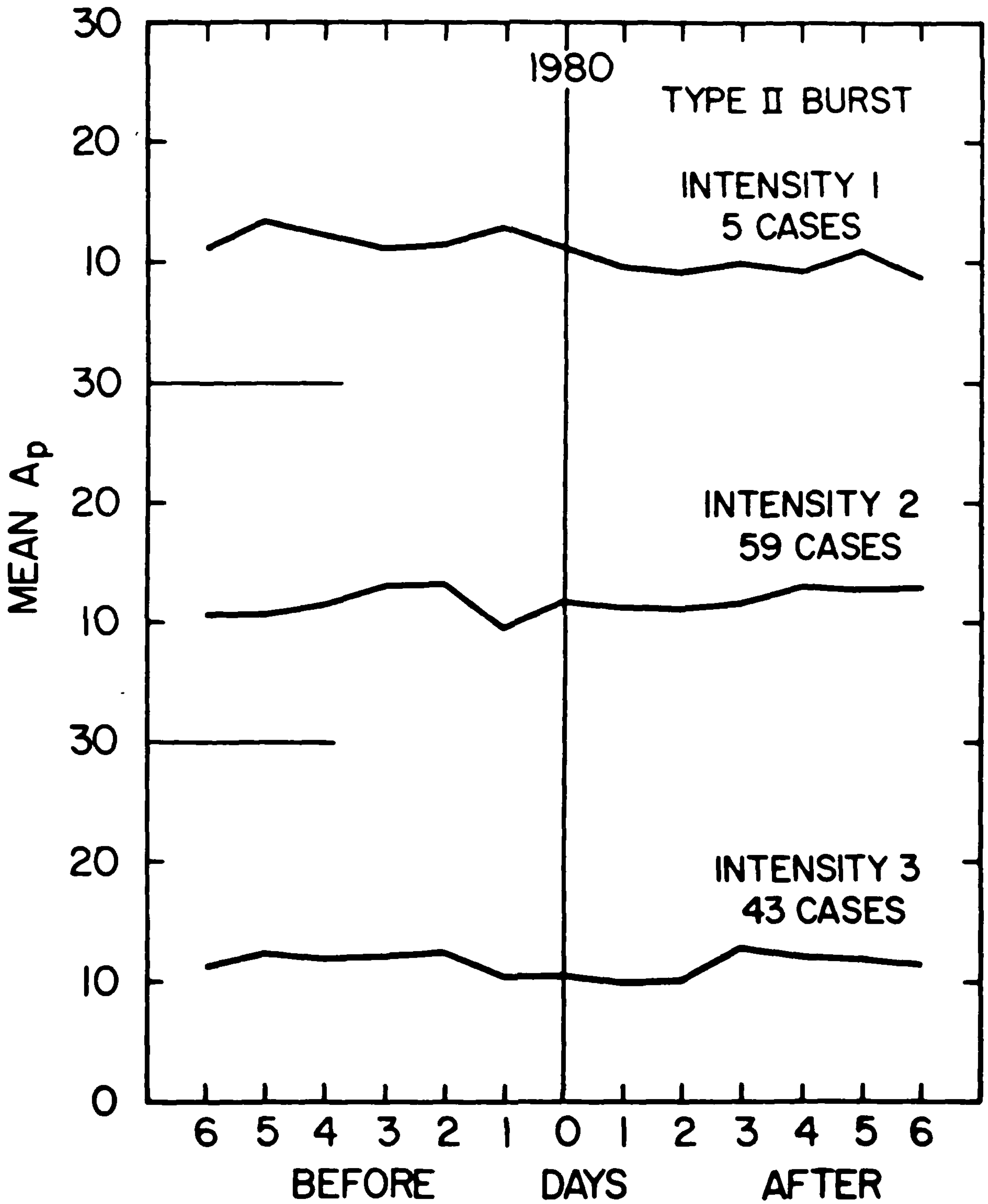

30
20
10
30
20
10
30
20
10
0
MEAN A_p
1980
TYPE II BURST
INTENSITY 1
5 CASES
INTENSITY 2
59 CASES
INTENSITY 3
43 CASES
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE
DAYS
AFTER

Fig. 2a

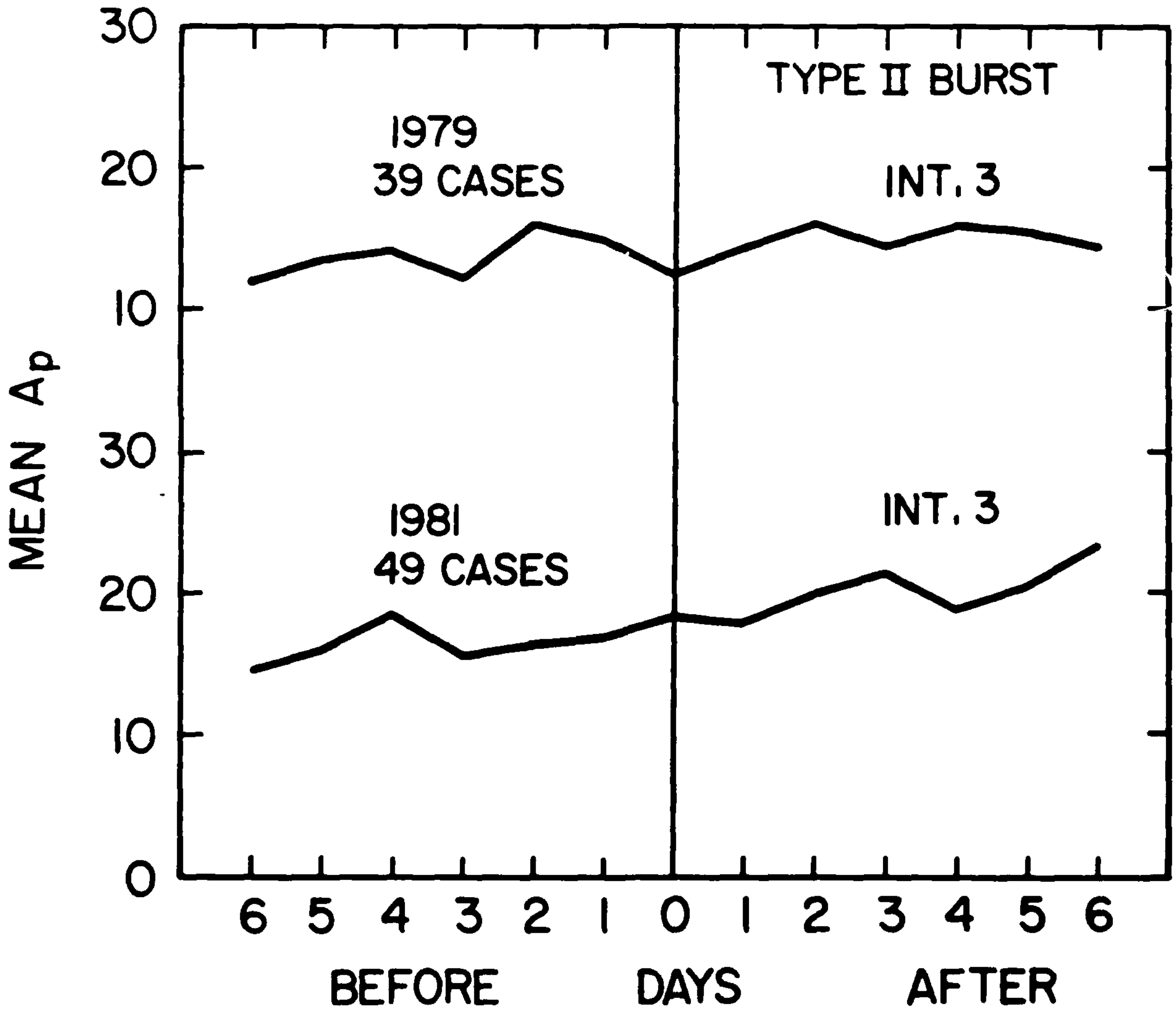

30
20
10
30
20
10
0
MEAN A_p
TYPE II BURST
1979
39 CASES
INT. 3
1981
49 CASES
INT. 3
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE DAYS AFTER

Fig. 2b

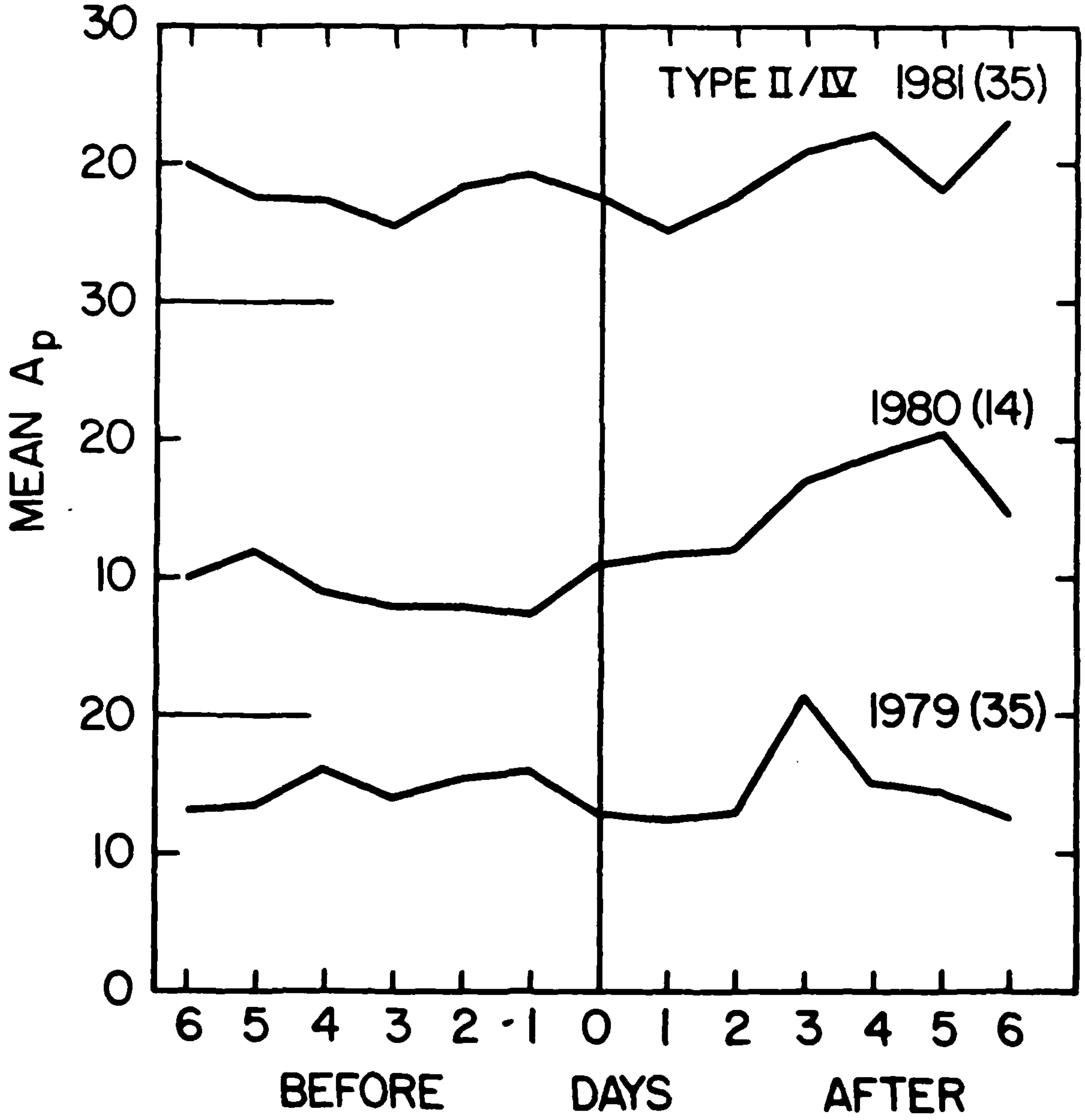

TYPE II/IV 1981 (35)
1980 (14)
1979 (35)
MEAN A_p
30
20
30
20
10
20
10
0
6 5 4 3 2 -1 0 1 2 3 4 5 6
BEFORE
DAYS
AFTER

Fig. 3

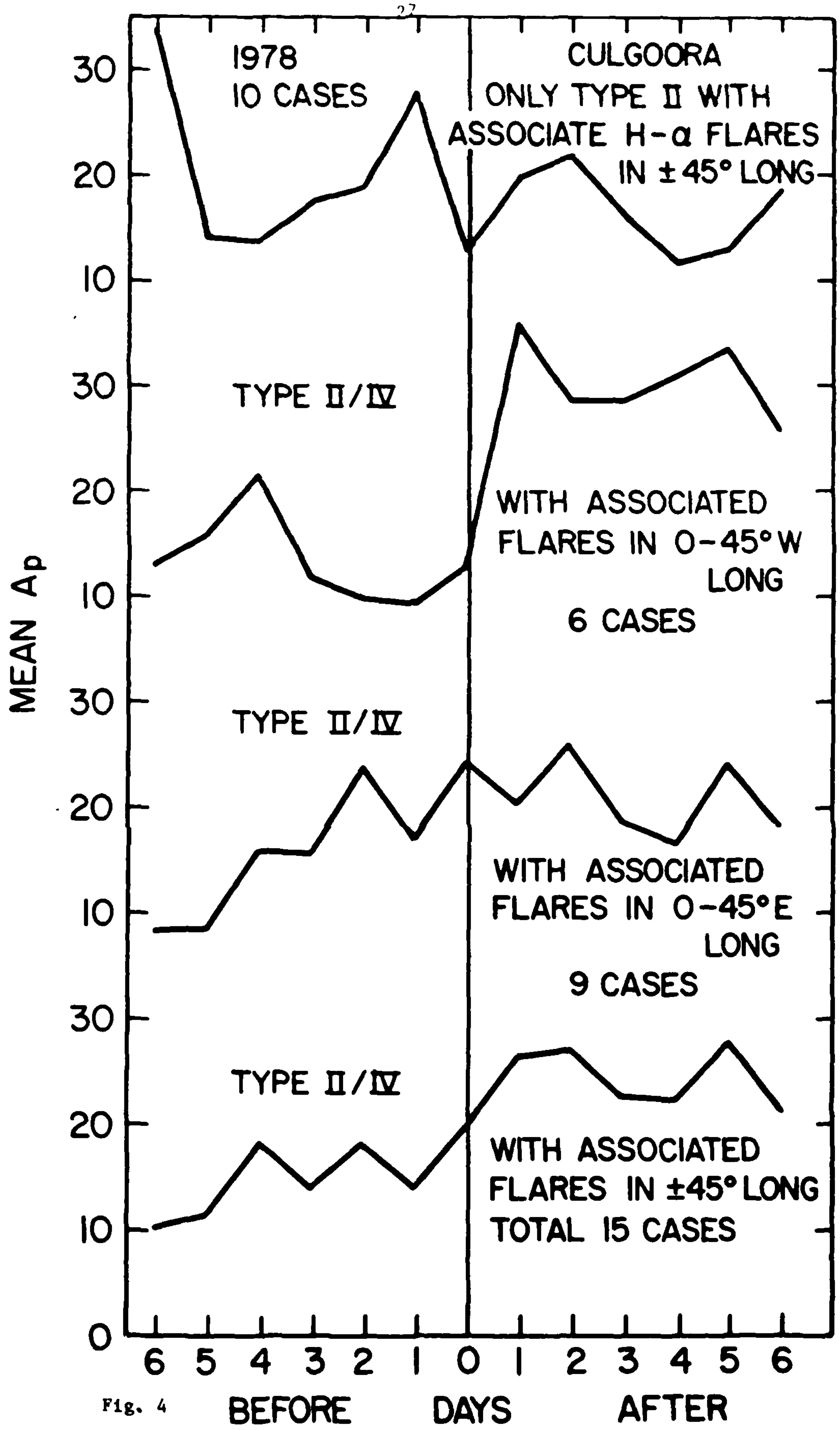
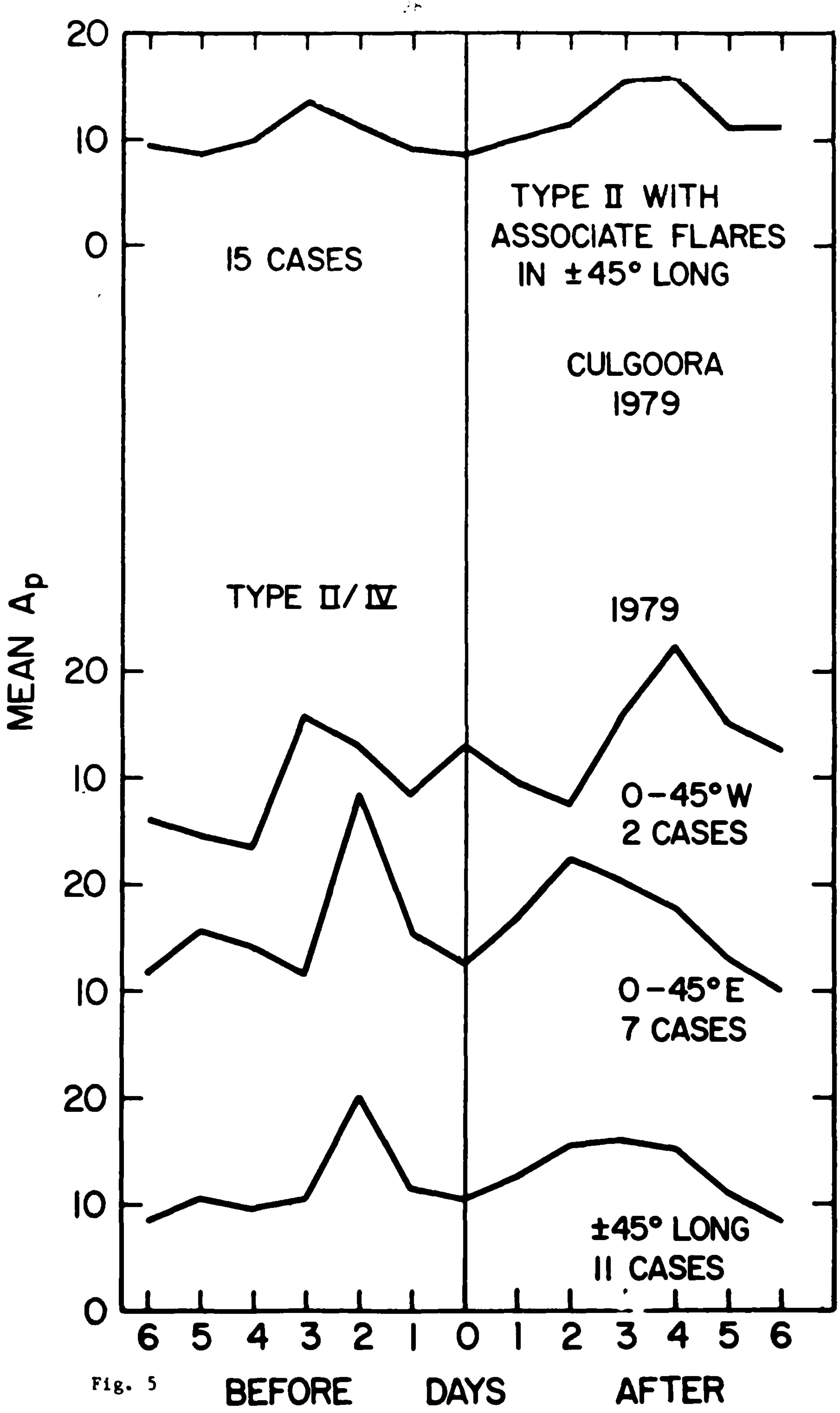

1978
10 CASES
CULGOORA
ONLY TYPE II WITH
ASSOCIATE H-α FLARES
IN ±45° LONG
TYPE II/IV
WITH ASSOCIATED
FLARES IN 0-45° W
LONG
6 CASES
TYPE II/IV
WITH ASSOCIATED
FLARES IN 0-45° E
LONG
9 CASES
TYPE II/IV
WITH ASSOCIATED
FLARES IN ±45° LONG
TOTAL 15 CASES
MEAN Ap
0
10
20
30
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE
DAYS
AFTER

Fig. 4



MEAN A_p
20
10
0
15 CASES
TYPE II WITH
ASSOCIATE FLARES
IN ±45° LONG
CULGOORA
1979
TYPE II/IV
1979
20
10
0–45°W
2 CASES
20
10
0–45°E
7 CASES
20
10
±45° LONG
11 CASES
0
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE DAYS AFTER

Fig. 5

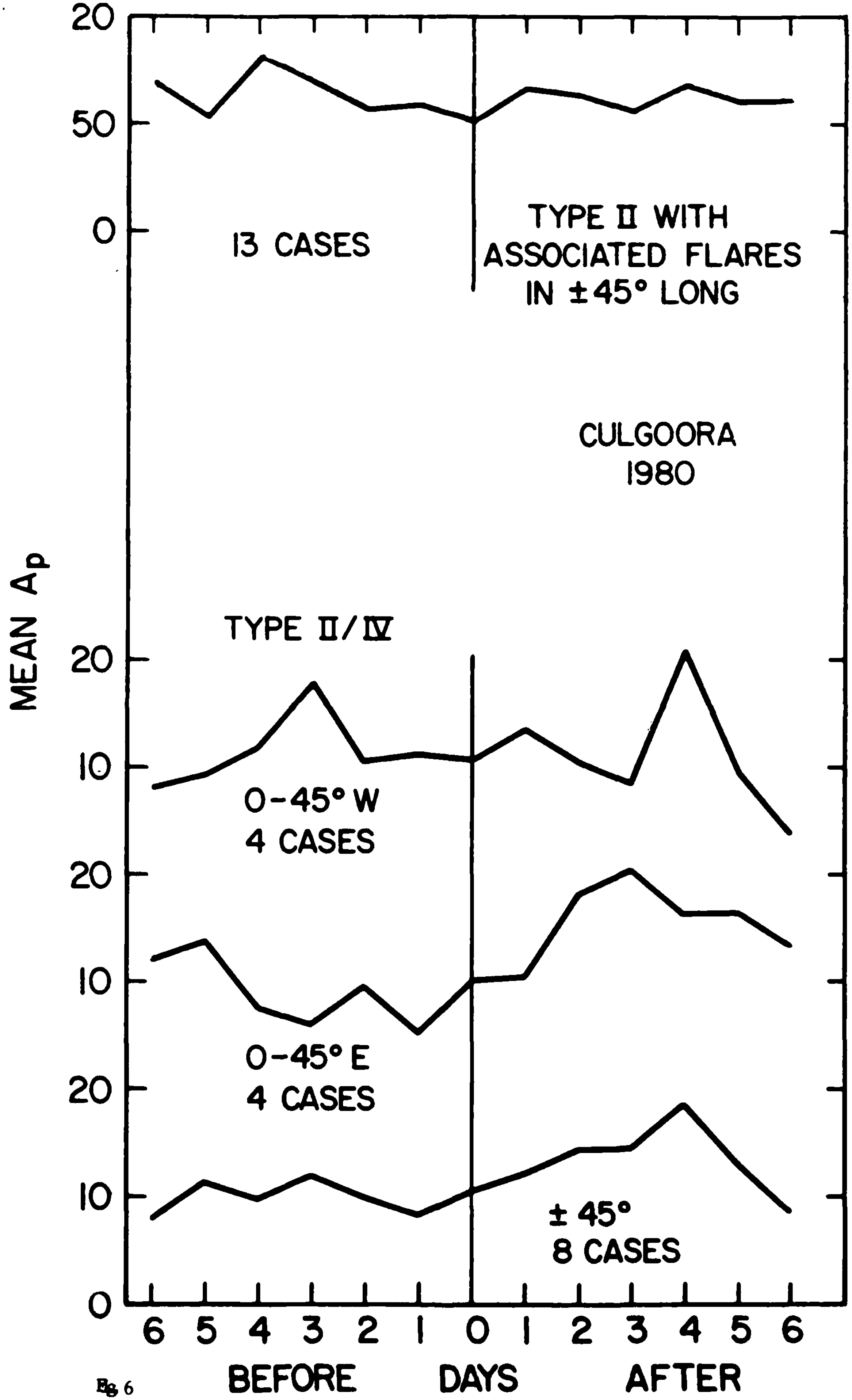

MEAN A_p
20
50
0
13 CASES
TYPE II WITH
ASSOCIATED FLARES
IN ±45° LONG
CULGOORA
1980
TYPE II/IV
20
10
0-45° W
4 CASES
20
10
0-45° E
4 CASES
20
10
0
± 45°
8 CASES
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE DAYS AFTER

Fig 6

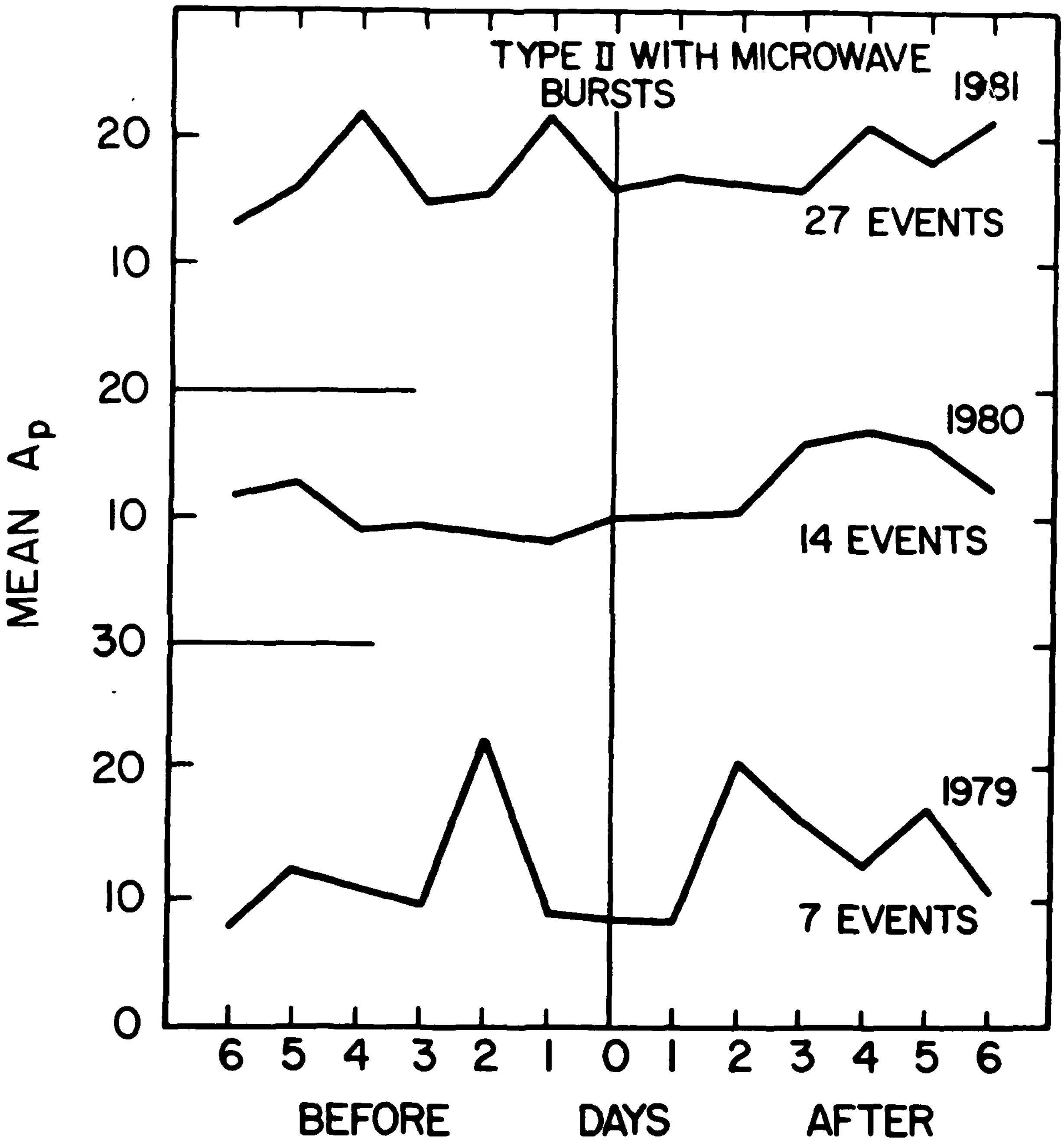

TYPE II WITH MICROWAVE BURSTS
1981
27 EVENTS
1980
14 EVENTS
1979
7 EVENTS
MEAN A_p
20
10
20
10
30
20
10
0
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE DAYS AFTER

Fig. 7

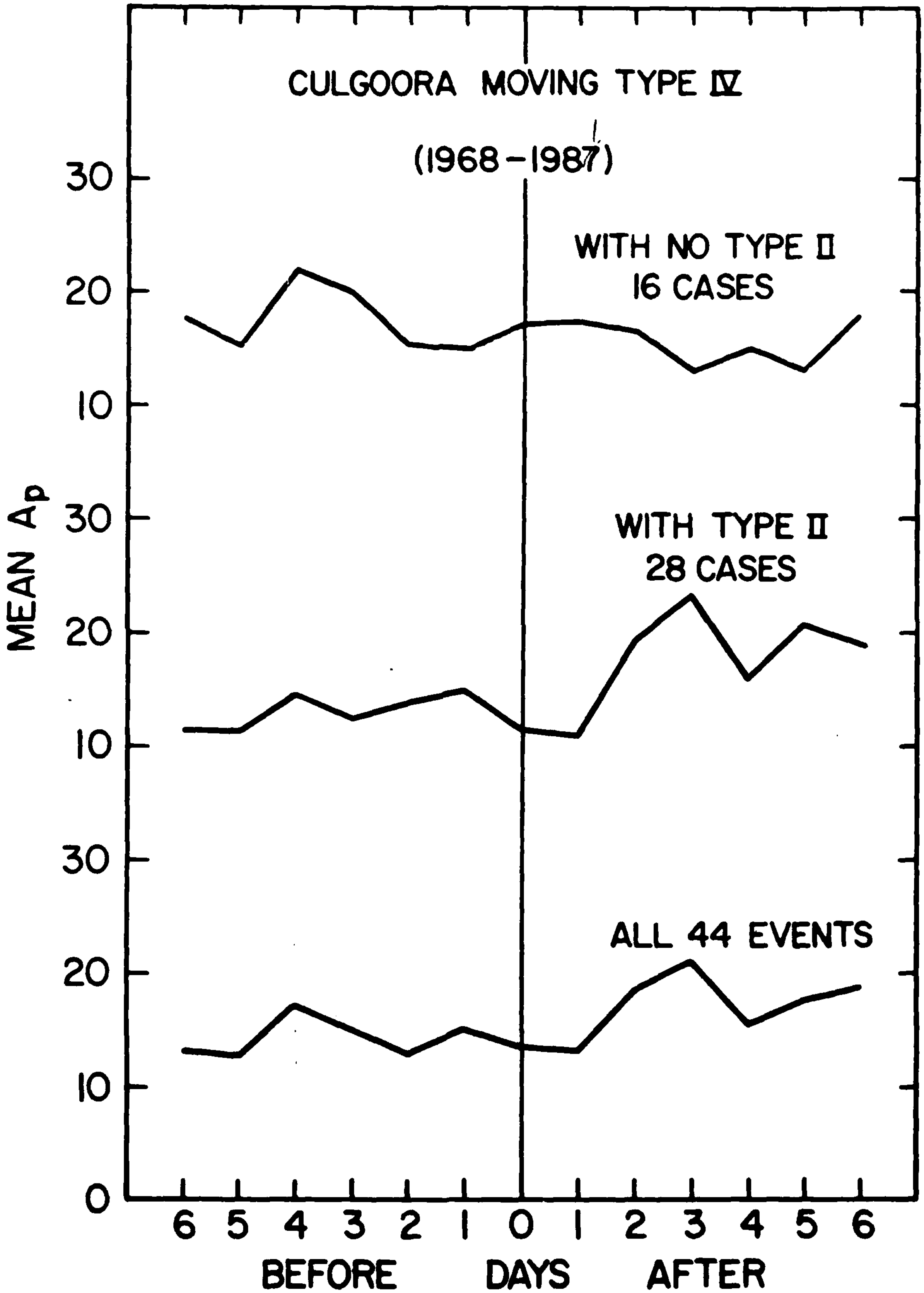

CULGOORA MOVING TYPE IV
(1968-1987)
WITH NO TYPE II
16 CASES
WITH TYPE II
28 CASES
ALL 44 EVENTS
MEAN A_p
30
20
10
0
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE DAYS AFTER

Fig. 8

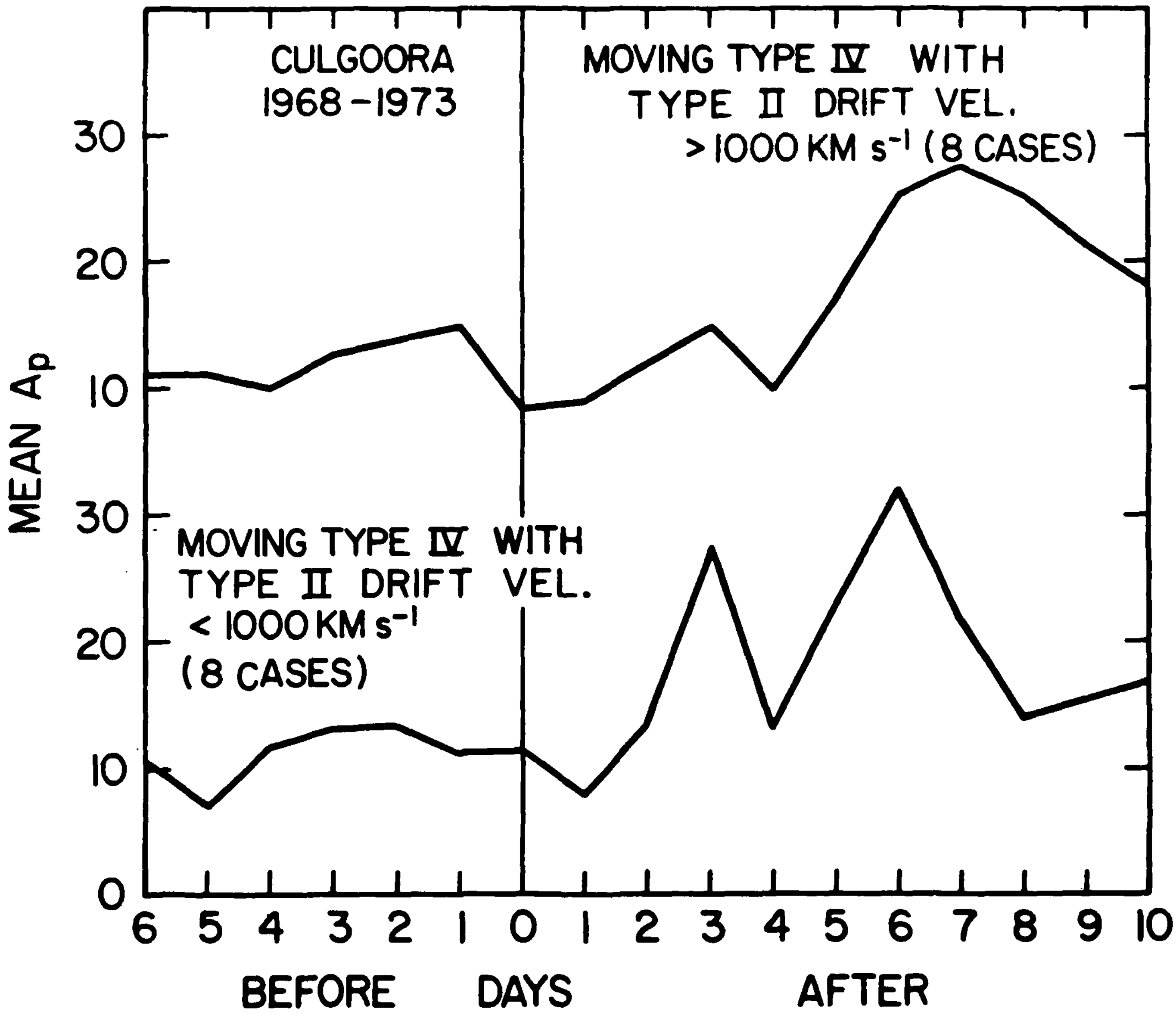

CULGOORA
1968 - 1973
MOVING TYPE IV WITH
TYPE II DRIFT VEL.
> 1000 KM s-1 (8 CASES)
MOVING TYPE IV WITH
TYPE II DRIFT VEL.
< 1000 KM s-1
(8 CASES)
MEAN Ap
30
20
10
30
20
10
0
6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 10
BEFORE DAYS AFTER

Fig. 9

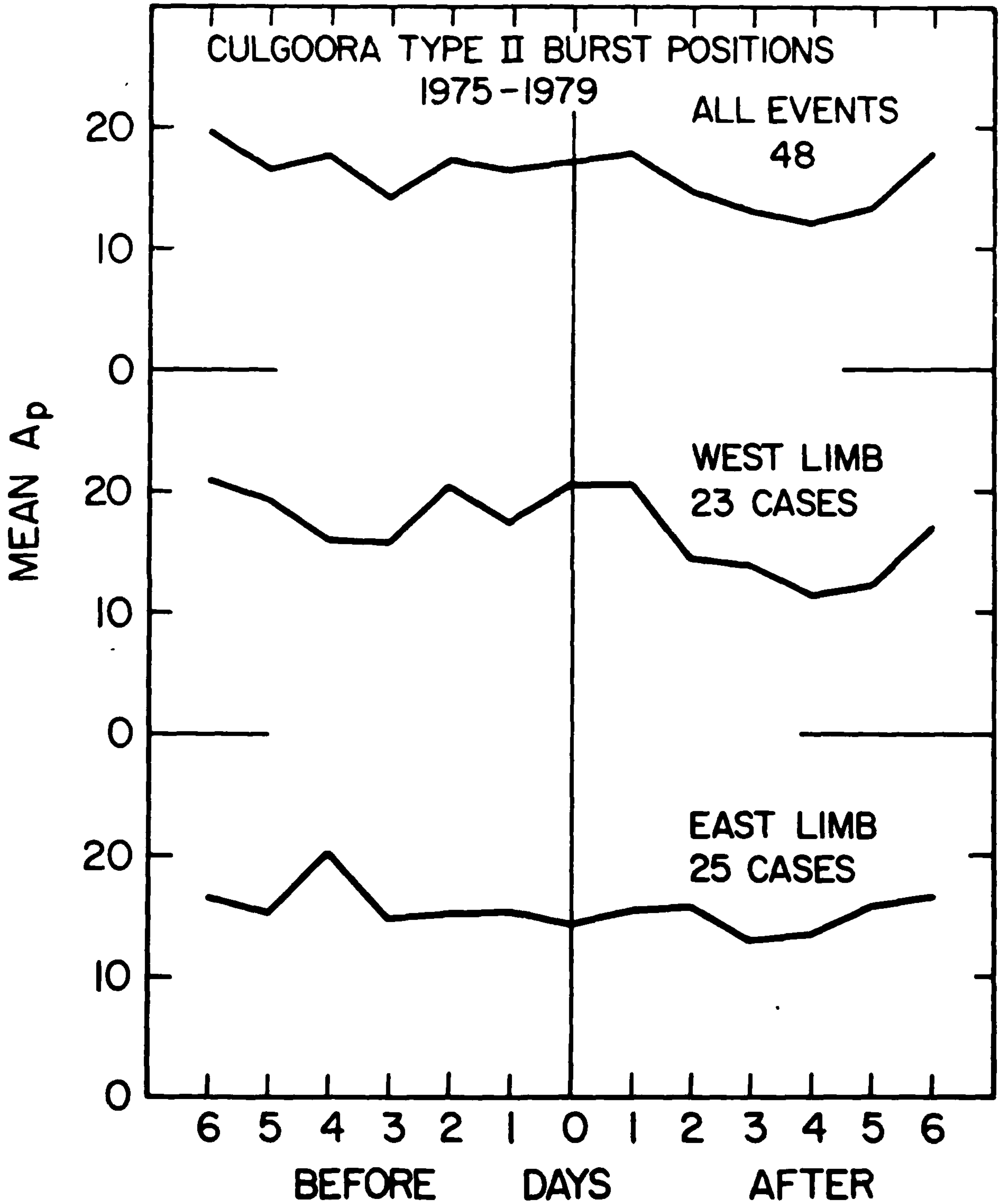

CULGOORA TYPE II BURST POSITIONS
1975-1979
ALL EVENTS
48
WEST LIMB
23 CASES
EAST LIMB
25 CASES
MEAN A_p
20
10
0
20
10
0
20
10
0
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE
DAYS
AFTER

Fig. 10

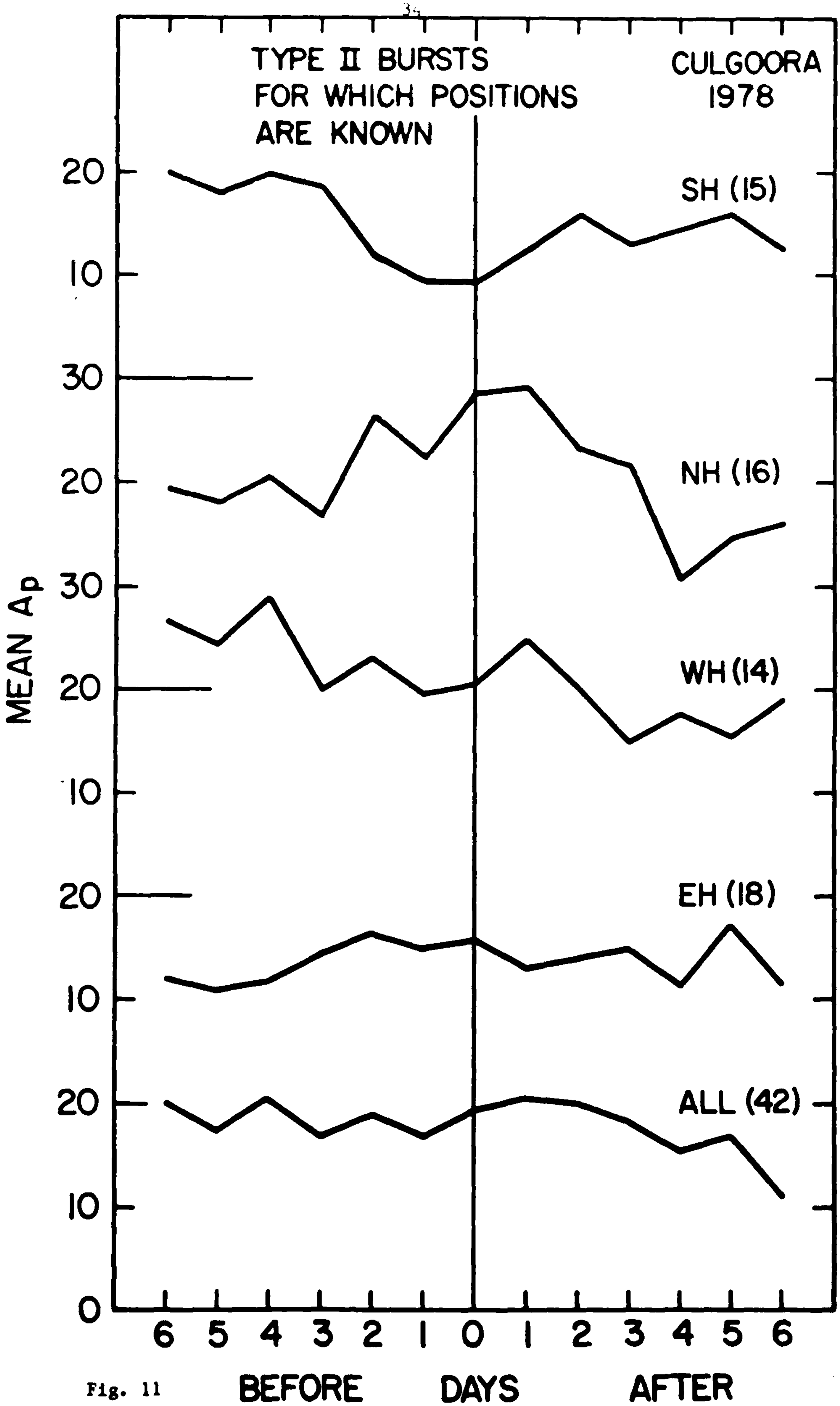

TYPE II BURSTS FOR WHICH POSITIONS ARE KNOWN
CULGOORA 1978
SH (15)
NH (16)
WH (14)
EH (18)
ALL (42)
MEAN A_p
20
10
30
20
30
20
10
20
10
20
10
0
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE
DAYS
AFTER

Fig. 11

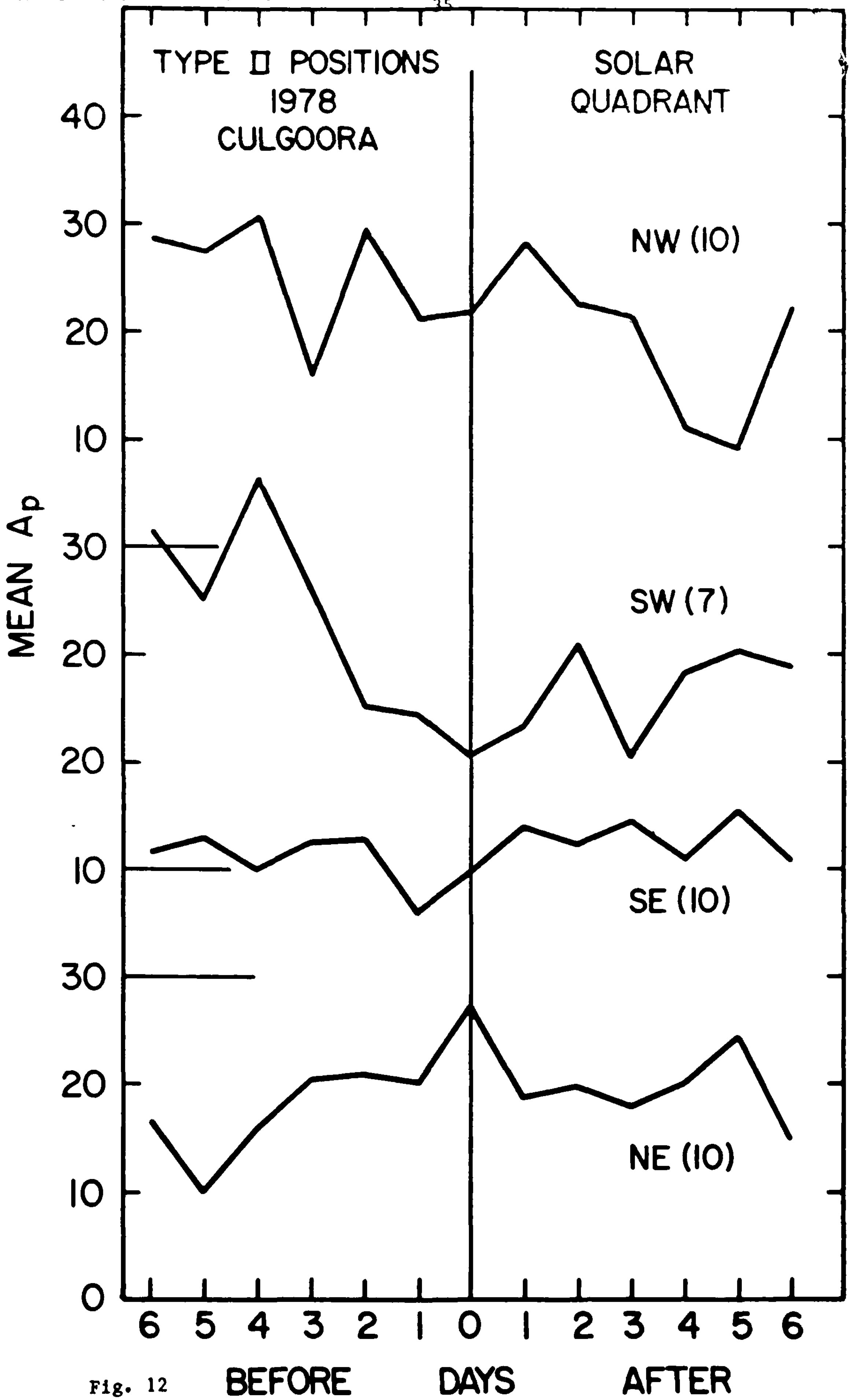

TYPE II POSITIONS
1978
CULGOORA
SOLAR
QUADRANT
NW (10)
SW (7)
SE (10)
NE (10)
MEAN A_p
40
30
20
10
30
20
20
10
30
20
10
0
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE
DAYS
AFTER

Fig. 12

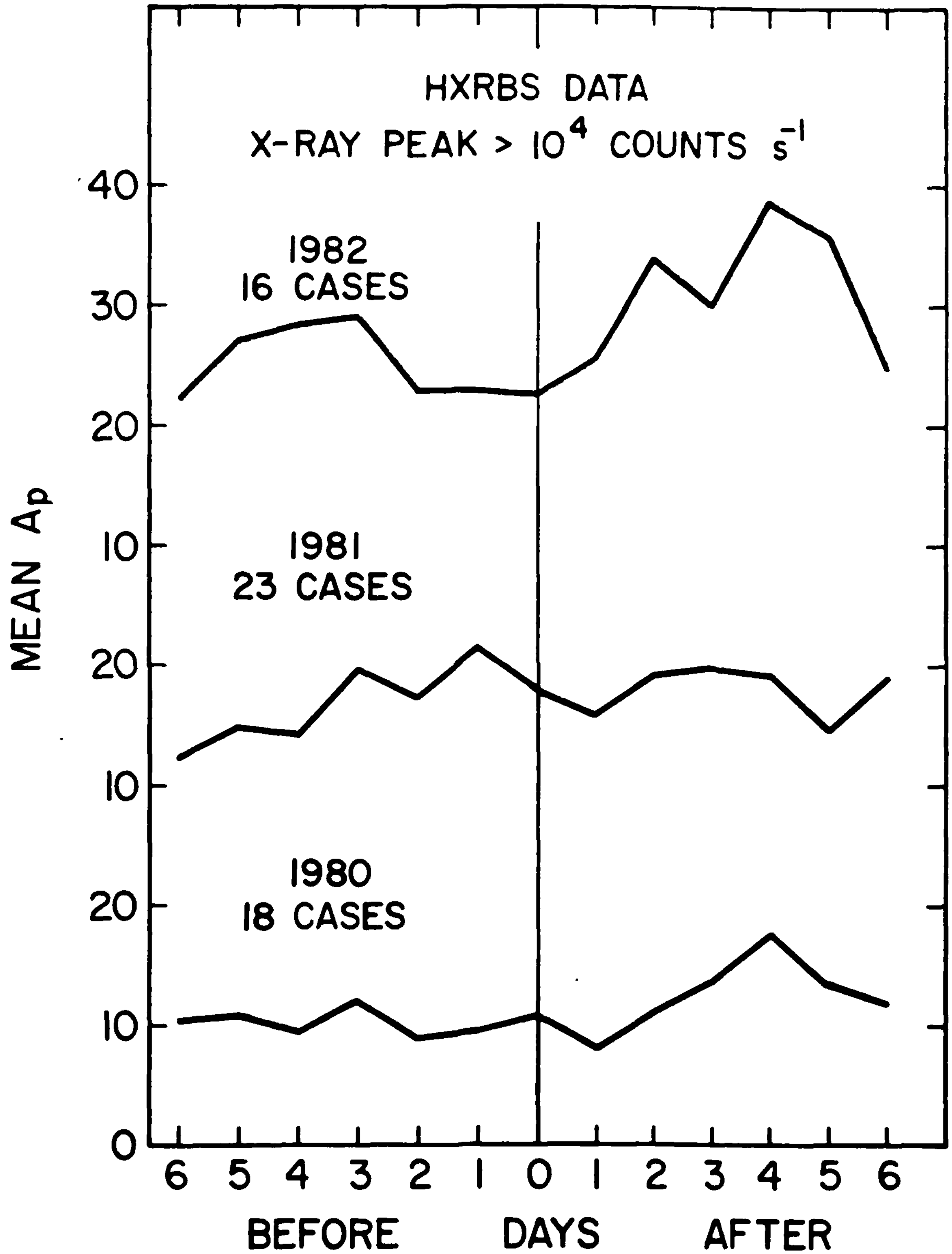

HXRBS DATA
X-RAY PEAK > 10^4 COUNTS s^-1
1982
16 CASES
1981
23 CASES
1980
18 CASES
MEAN Ap
40
30
20
10
20
10
20
10
0
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE DAYS AFTER

Fig. 13

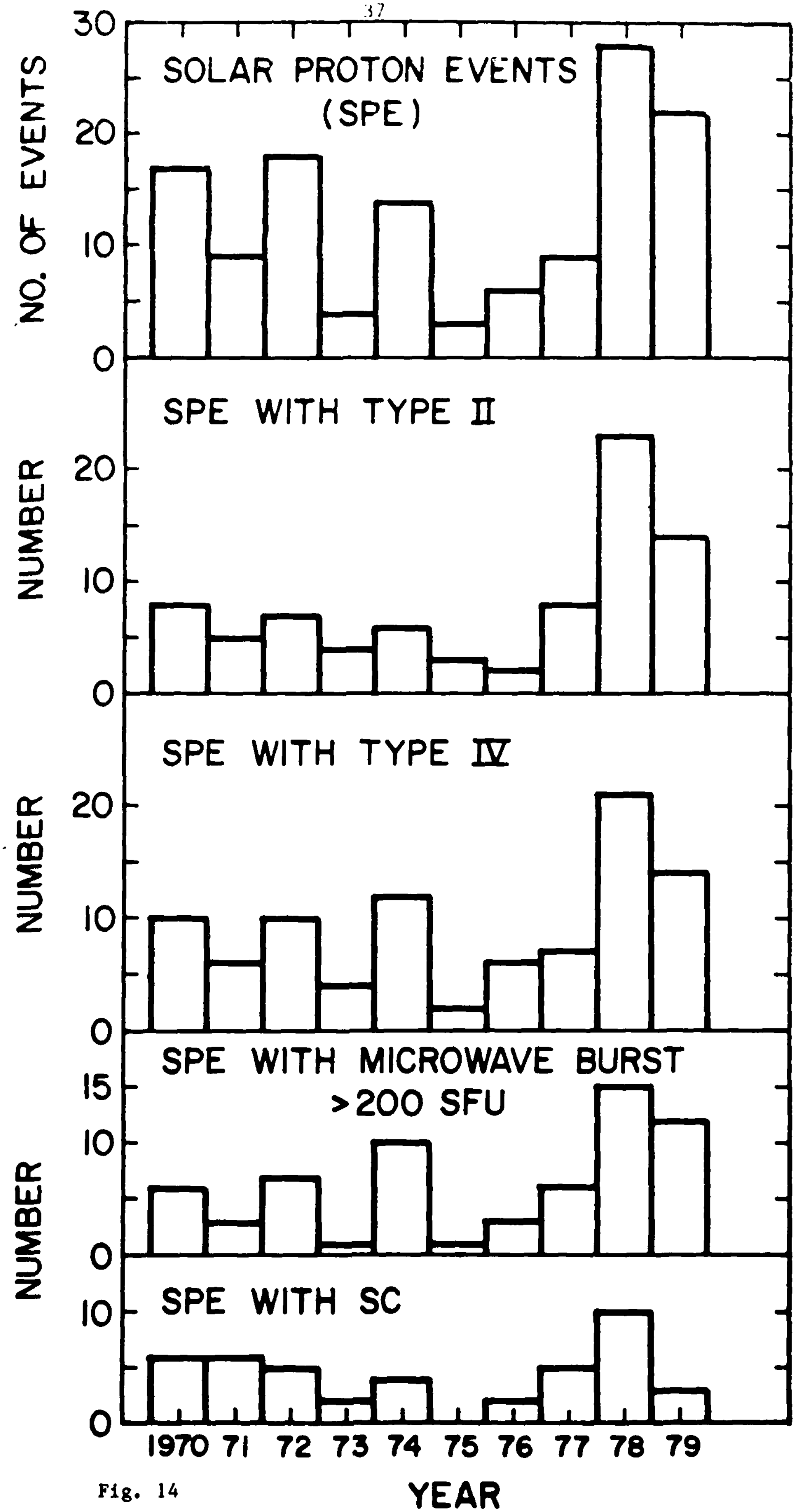

SOLAR PROTON EVENTS
(SPE)
NO. OF EVENTS
30
20
10
0
SPE WITH TYPE II
NUMBER
20
10
0
SPE WITH TYPE IV
NUMBER
20
10
0
SPE WITH MICROWAVE BURST
>200 SFU
15
10
0
NUMBER
SPE WITH SC
10
0
1970 71 72 73 74 75 76 77 78 79
YEAR

Fig. 14

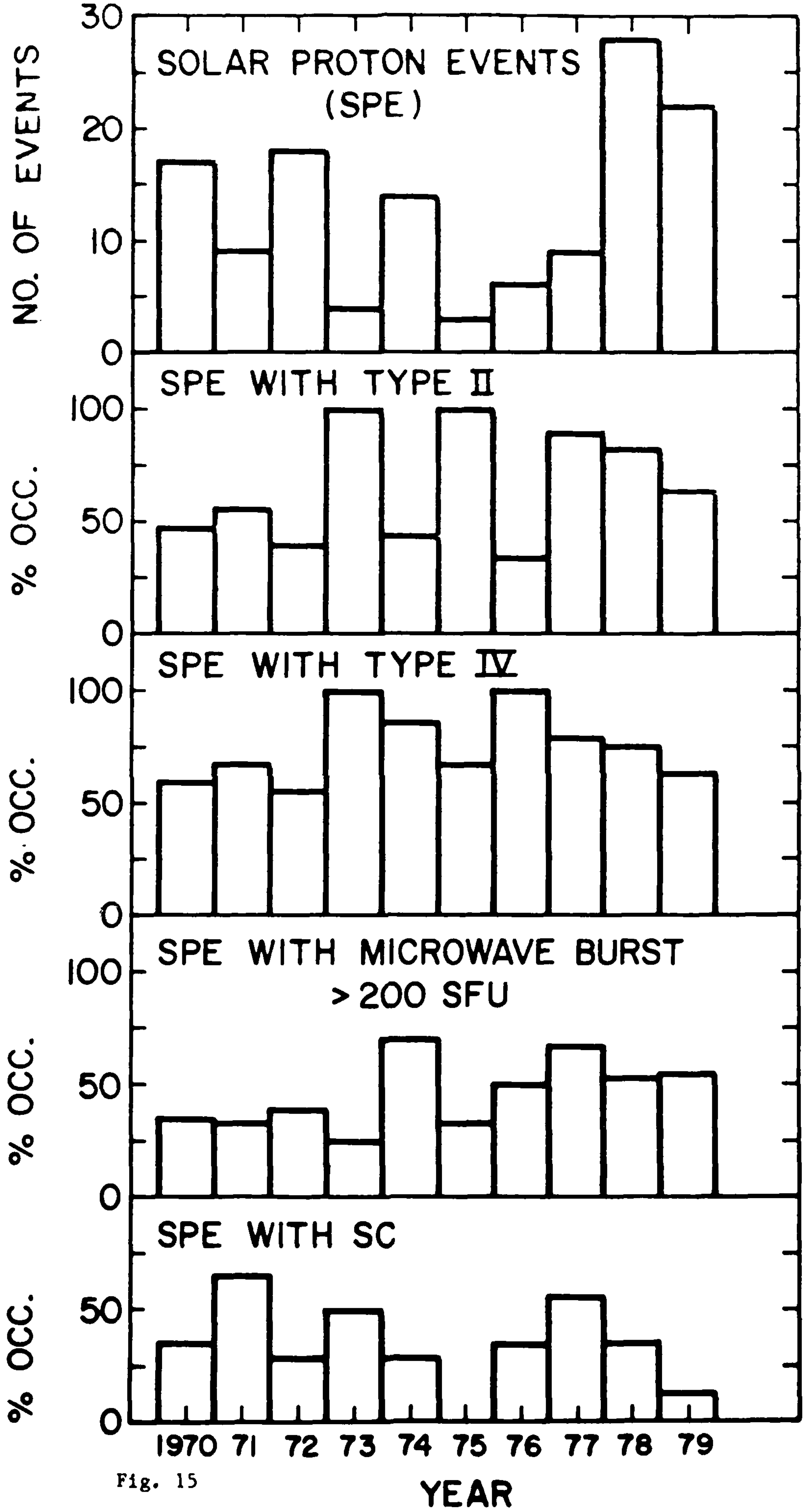
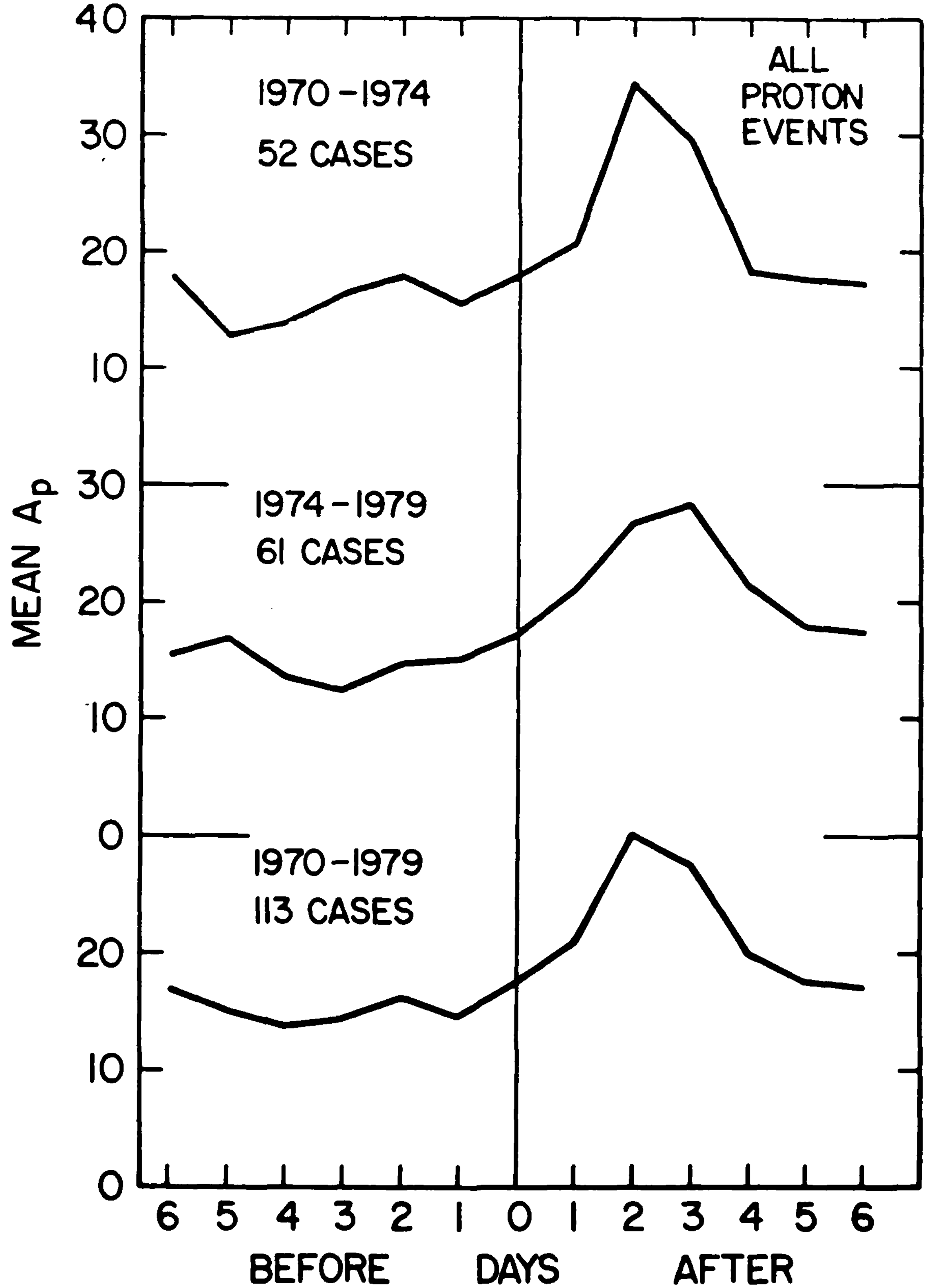

SOLAR PROTON EVENTS (SPE)
NO. OF EVENTS
0
10
20
30
SPE WITH TYPE II
% OCC.
0
50
100
SPE WITH TYPE IV
% OCC.
0
50
100
SPE WITH MICROWAVE BURST >200 SFU
% OCC.
0
50
100
SPE WITH SC
% OCC.
0
50
1970 71 72 73 74 75 76 77 78 79
YEAR

Fig. 15



40
30
20
10
30
20
10
0
20
10
0
MEAN A_p
1970 - 1974
52 CASES
ALL
PROTON
EVENTS
1974 - 1979
61 CASES
1970 - 1979
113 CASES
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE
DAYS
AFTER

Fig. 16

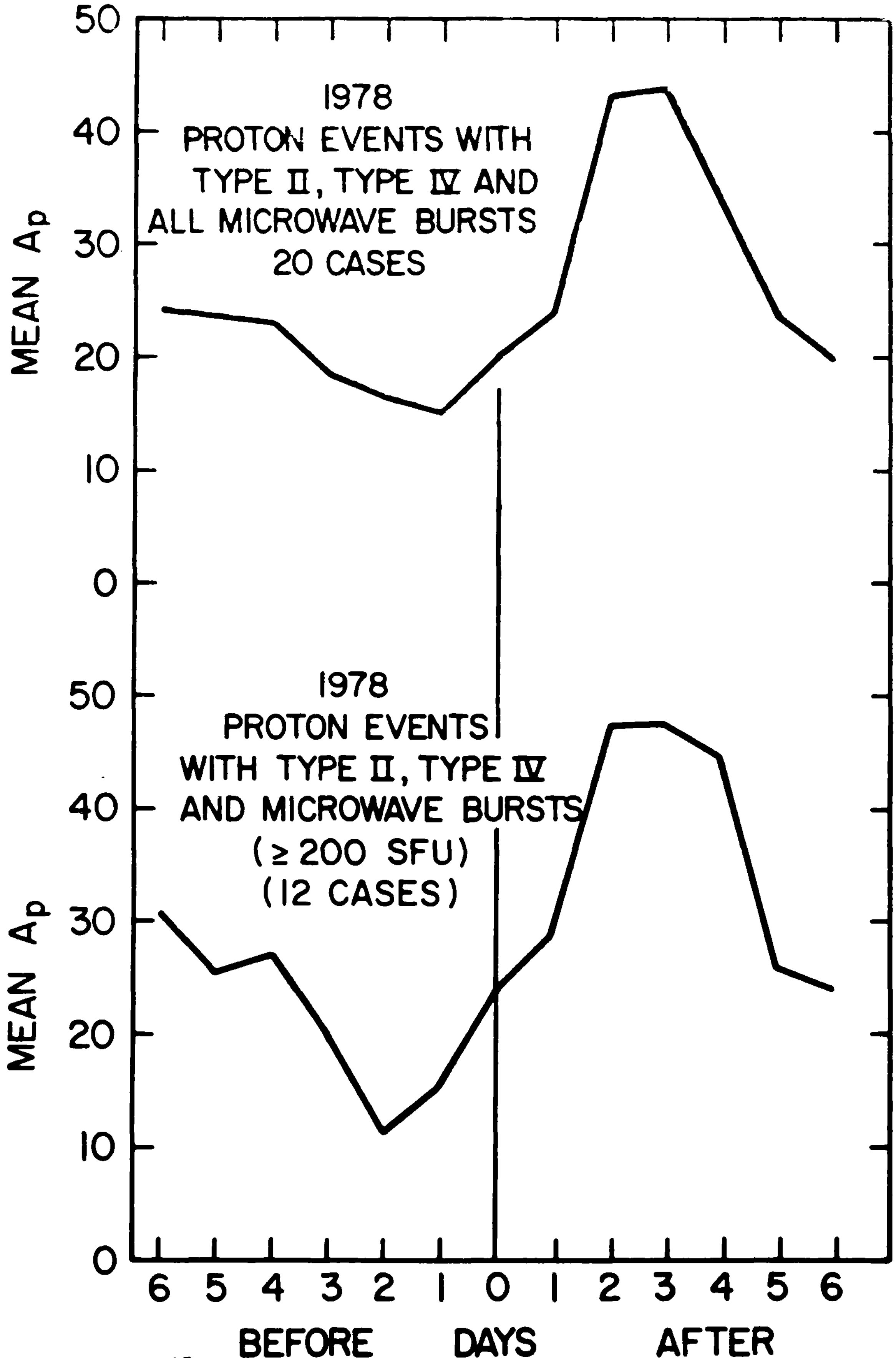

1978
PROTON EVENTS WITH
TYPE II, TYPE IV AND
ALL MICROWAVE BURSTS
20 CASES
MEAN A_p
50
40
30
20
10
0
1978
PROTON EVENTS
WITH TYPE II, TYPE IV
AND MICROWAVE BURSTS
(≥ 200 SFU)
(12 CASES)
MEAN A_p
50
40
30
20
10
0
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE
DAYS
AFTER

Fig. 17

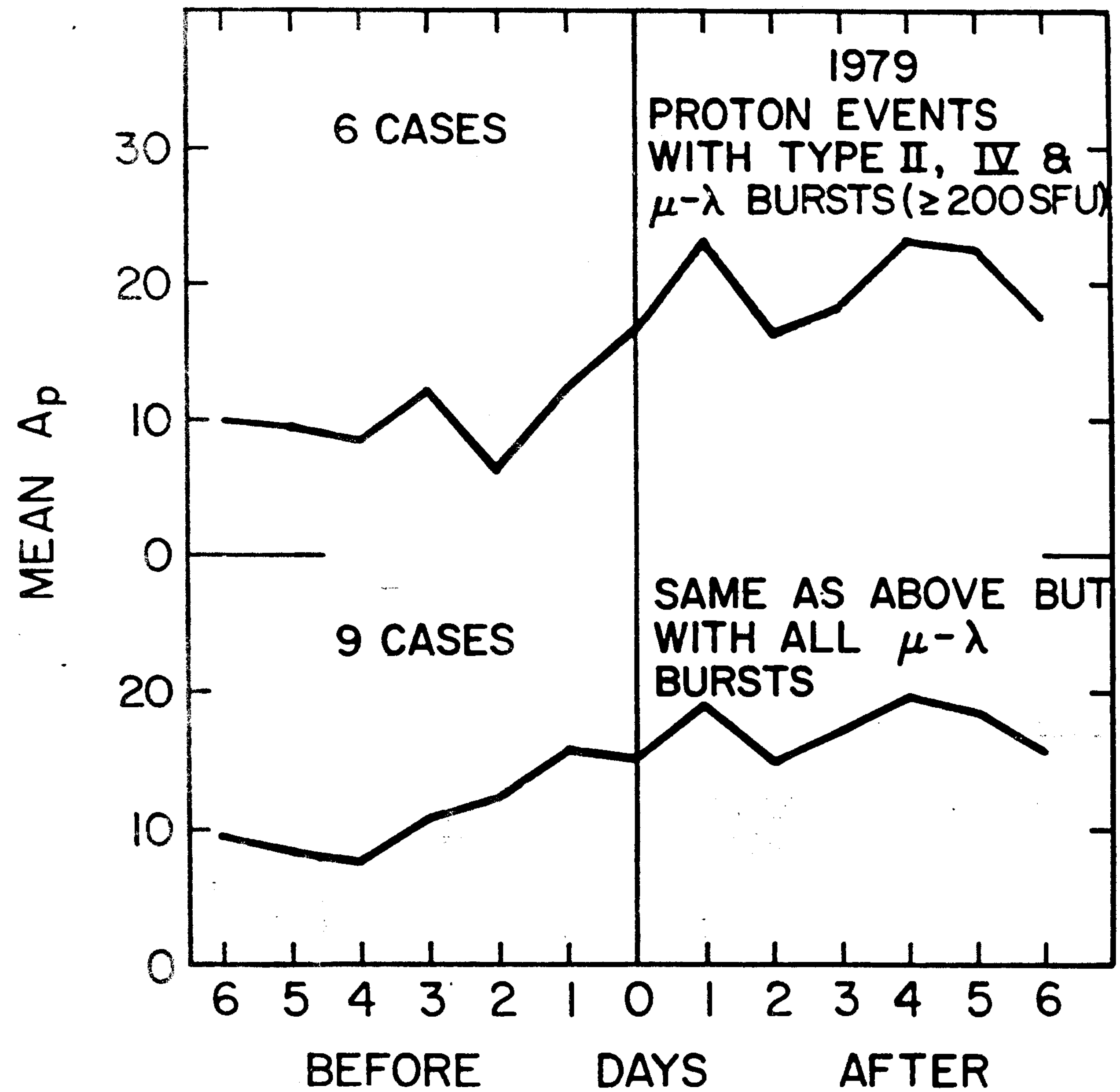
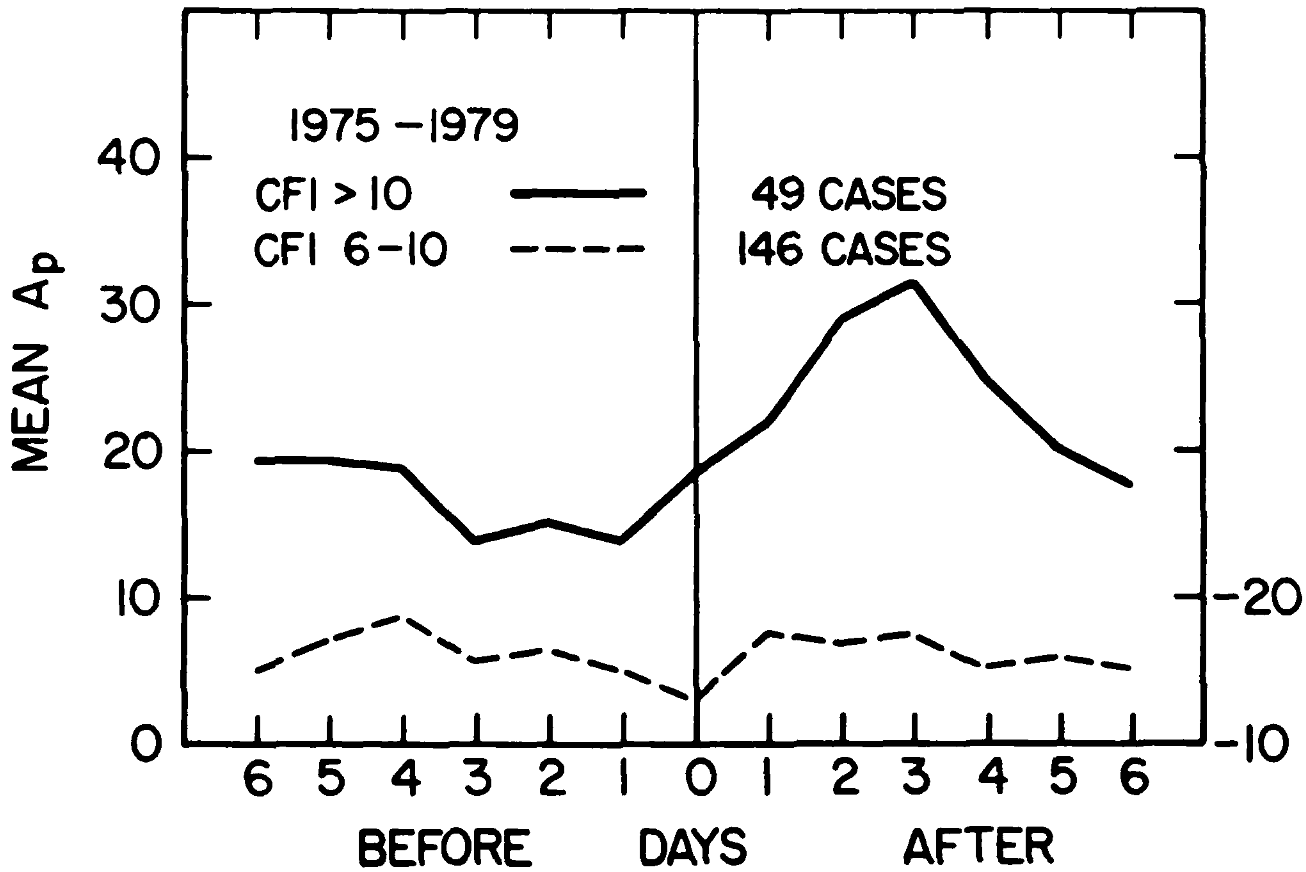

1979
PROTON EVENTS
WITH TYPE II, IV &
μ-λ BURSTS (≥200 SFU)
6 CASES
SAME AS ABOVE BUT
WITH ALL μ-λ
BURSTS
9 CASES
MEAN A_p
30
20
10
0
20
10
0
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE
DAYS
AFTER

Fig. 18



1975 – 1979
CFI > 10
49 CASES
CFI 6–10
146 CASES
MEAN A_p
40
30
20
10
0
–20
–10
6 5 4 3 2 1 0 1 2 3 4 5 6
BEFORE
DAYS
AFTER

Fig. 19